Update on the Nested Hall Thruster Subsystem for the NextSTEP XR-100 Program

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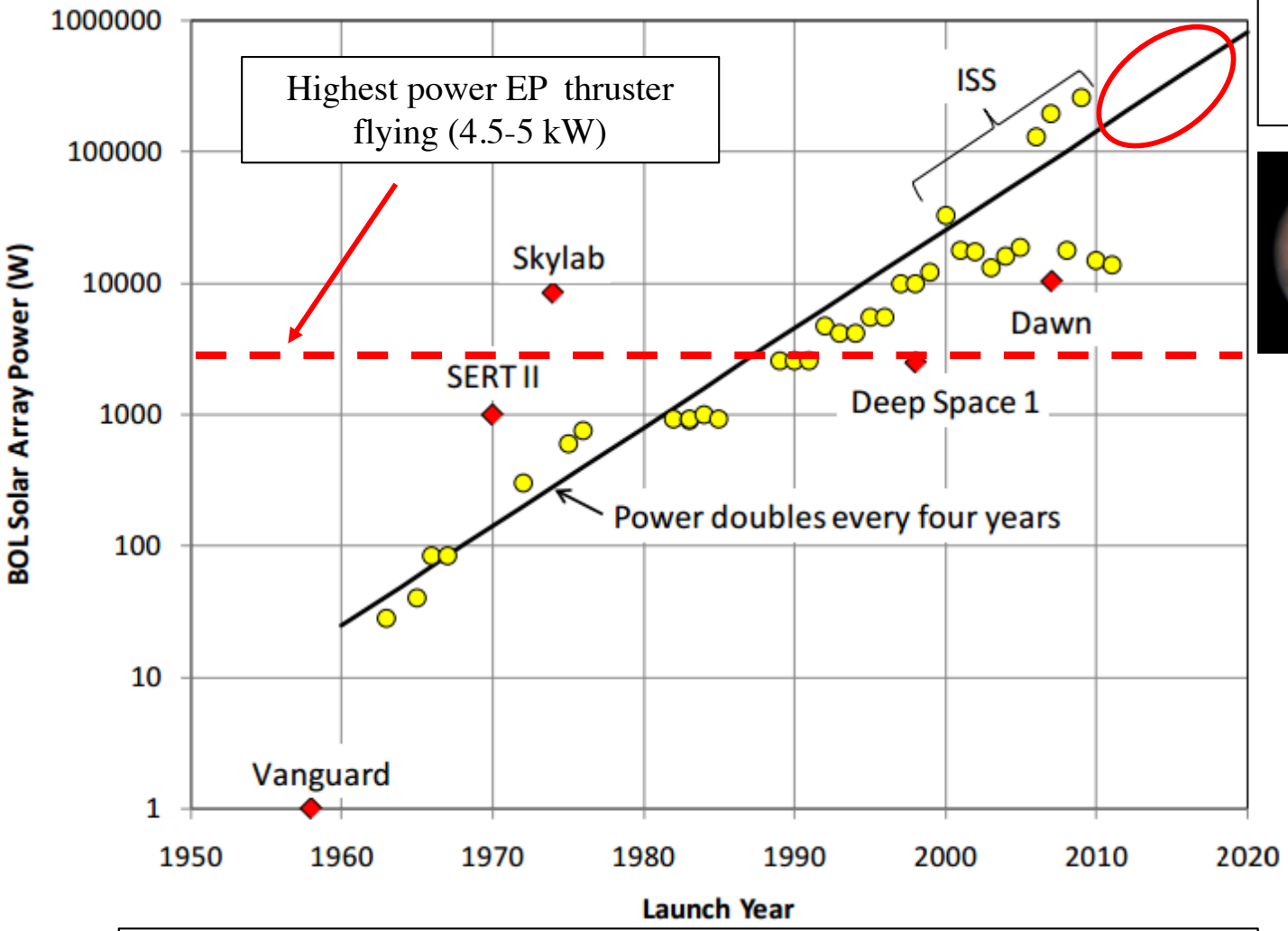
Jet Propulsion Laboratory, California Institute of Technology

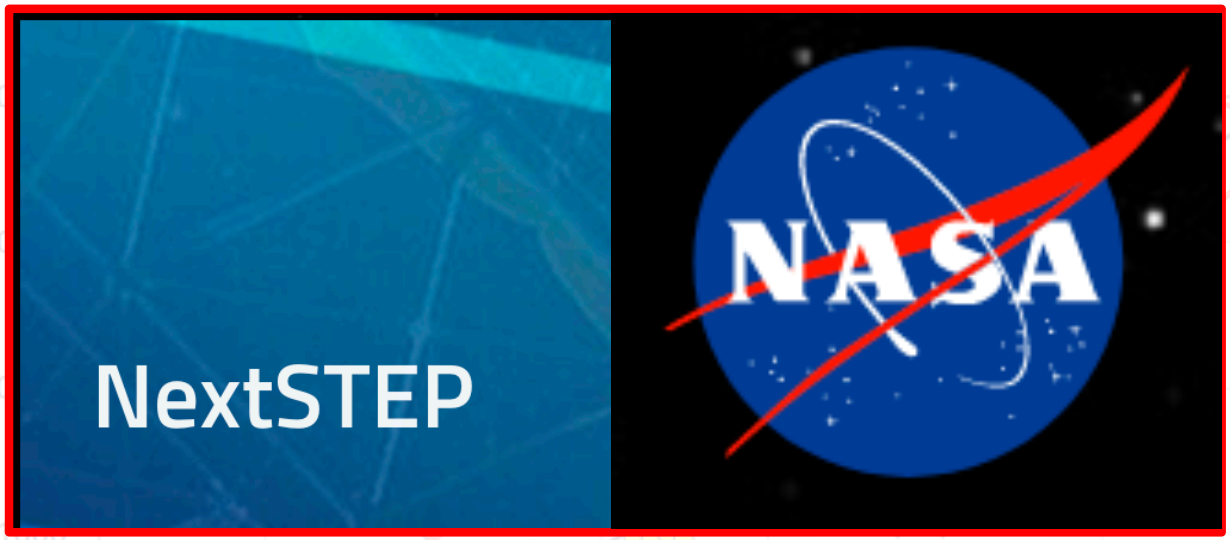
Available solar power in space is increasing rapidly



Cargo and crewed missions to Mars and moons

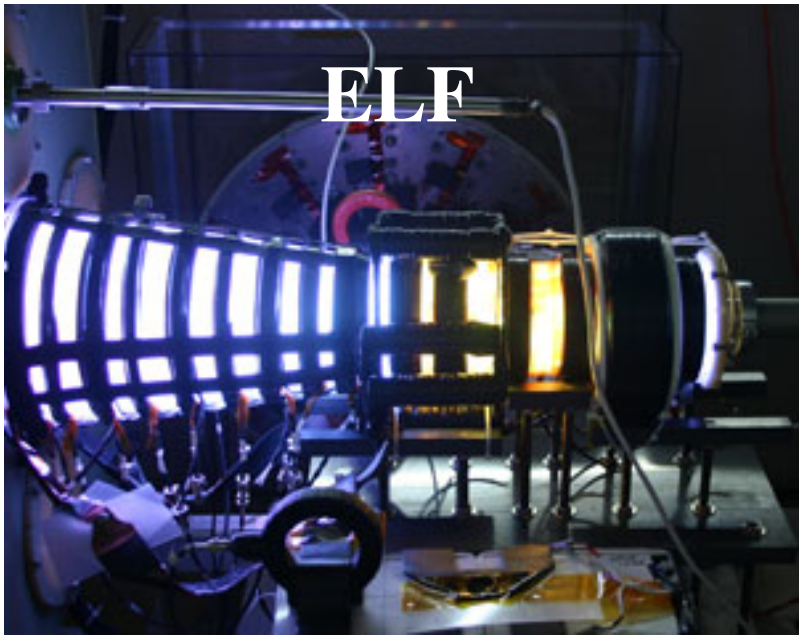
There is a need for next-generation electric propulsion systems capable of processing this power

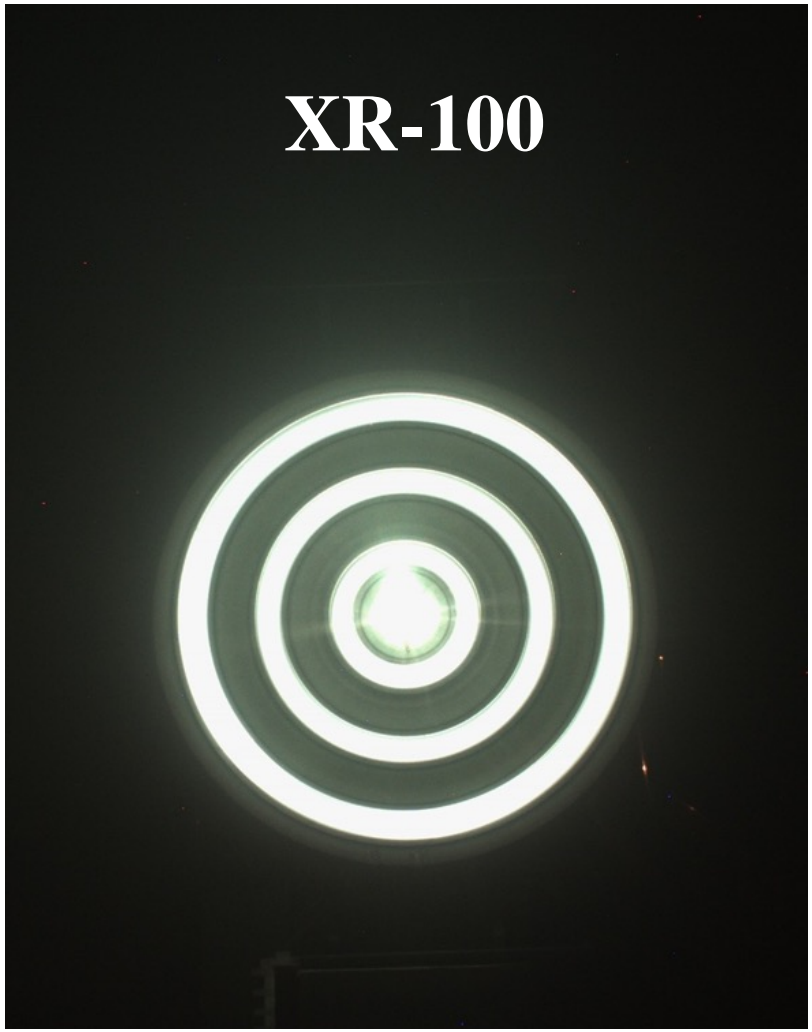
Available solar power in space is increasing rapidly



Metric		XR-100 Goal
Req.	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Objective	Specific Impulse	~2,000 to ~5,000 s
	Thrust per thruster	> 5 N
	Operational lifetime capability	> 10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System kg/kW	< 5 kg/kW

Three contracts selected for NextSTEP program

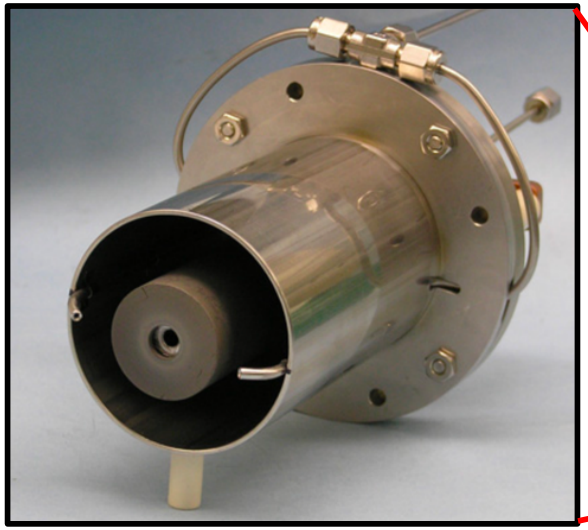




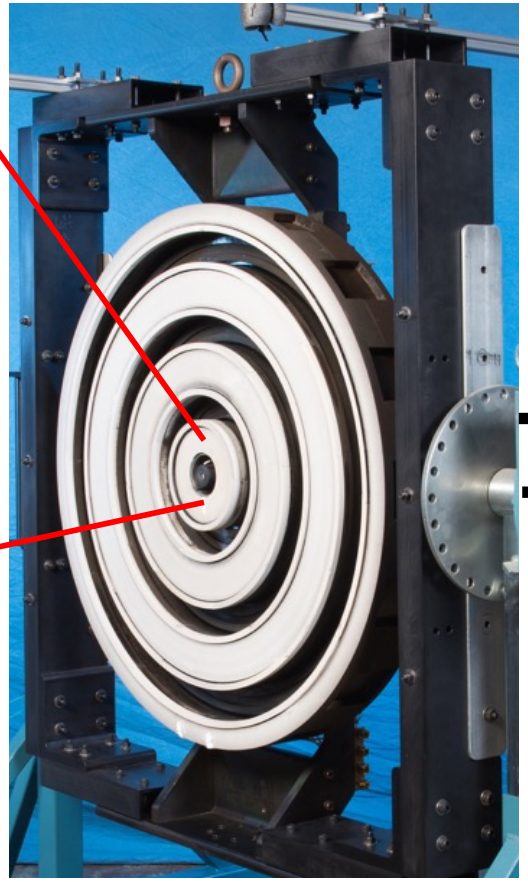
The XR-100 system

Propulsion element

300 A LaB_6 cathode (JPL)



X3 Nested Hall thruster (UM)



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Power/flow element

XFC (AR)

100 kW PPU (AR)

The XR-100 system

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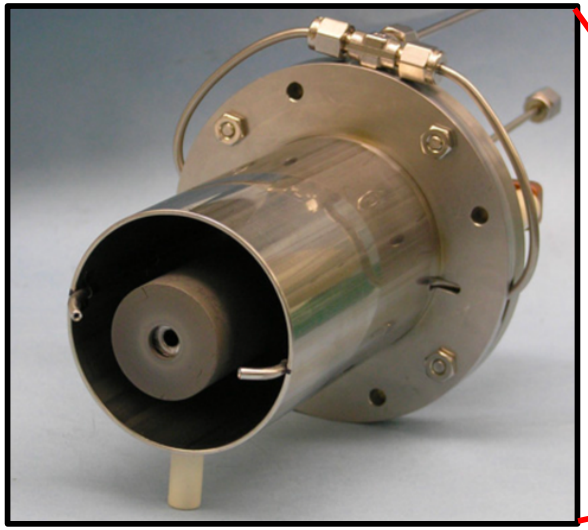

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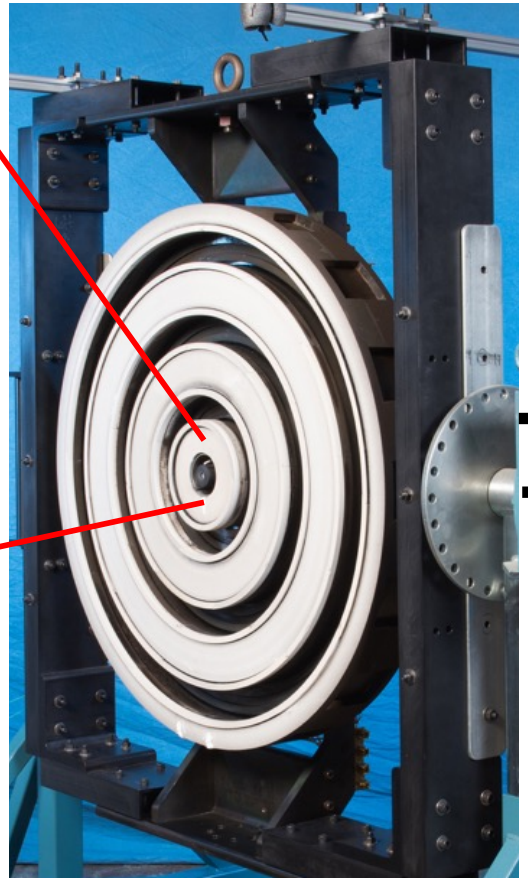

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Power/flow element

XFC (AR)

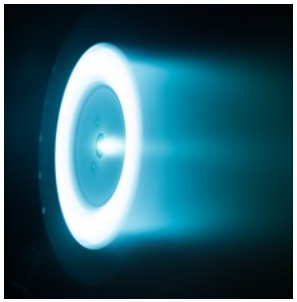
100 kW PPU (AR)

X3: Propulsion element for the XR-100 system

- **Merits and history of the X3**
- **Year 1 and 2 activities**
- **Remaining risk reduction activities**

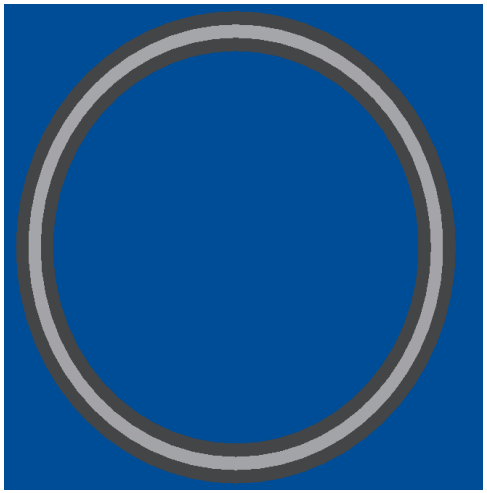
Motivation for nested Hall thrusters (NHT)

Hall effect thrusters (4.5-12.5 kW)

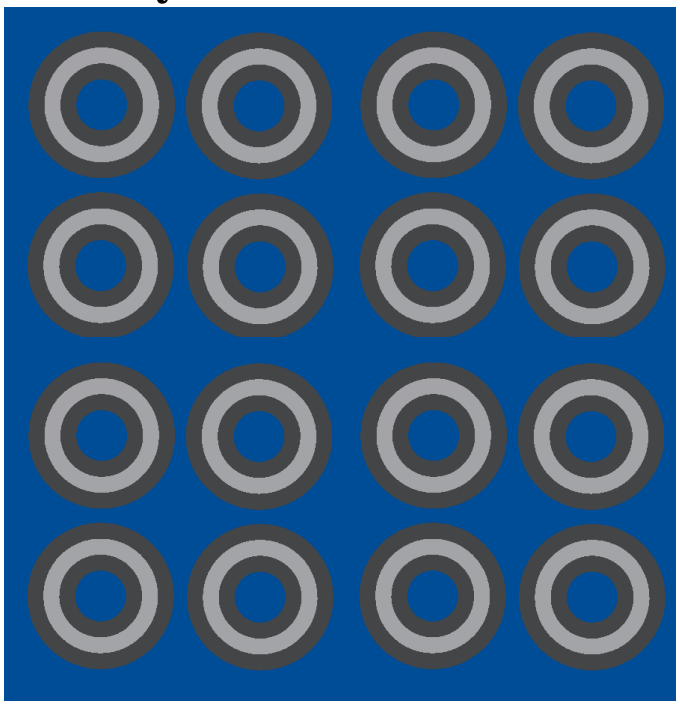


- High level of maturity
- Decades of heritage

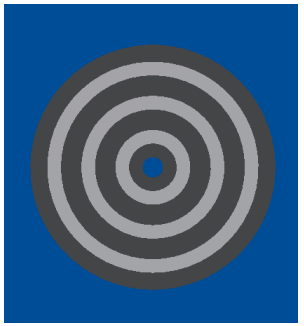
Scale a single channel



Array of smaller thrusters

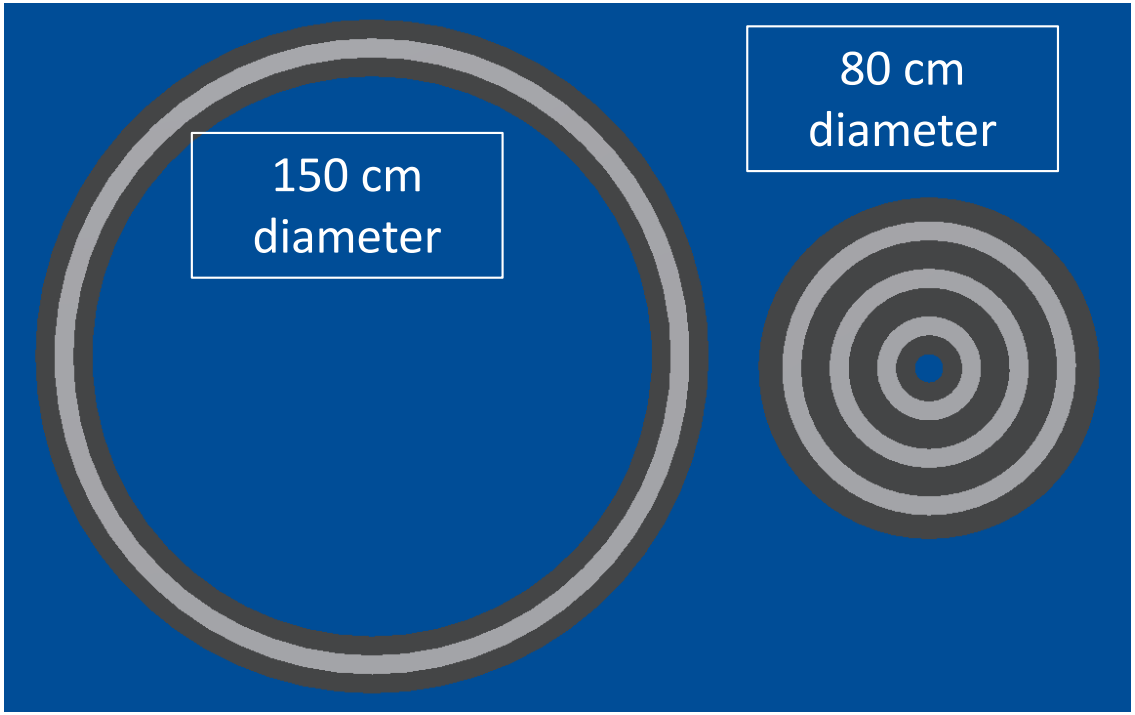


3 nested channels



Motivation for nested Hall thrusters (NHT)

200 kW system example of nesting



2.425 kg/kW at 300 V

1.85 kg/kW at 300 V

Nested Hall thrusters (X3) offer mass savings, improved throttling, and redundancy*

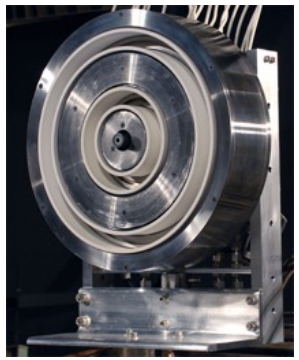
*S. Hall, B. Jorns, A. Gallimore, and R. Hofer. AIAA-2017-4729

X3 design specifications

Power	2-200 kW
Efficiency	> 60%
Thrust	0.2 N– 10 N
Specific impulse	1550 – 3500 s on **xenon**
Diameter	80 cm
Mass	250 kg
Cooling	Passive

Development history of X3

2009-2013 X2, 10 kW, two channel nested Hall thruster built and tested at UM



2013 X3 fired for first time at 30-kW at UM

2016 NextSTEP program awarded to Aerojet Rocketdyne

1999-2011 NASA program to investigate 50 kW-class, high-efficiency Hall thrusters

2009-2012 X3 designed and built by AFRL, AFOSR, JPL, NASA Glenn, and UM

2013-2015 X3 tested below 30 kW at UM. Efficiencies and performance below predictions

Challenges for X3 at beginning of XR-100 program

Metric		XR-100 Goal
Req.	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Objective	Specific Impulse	~2,000 to ~5,000 s
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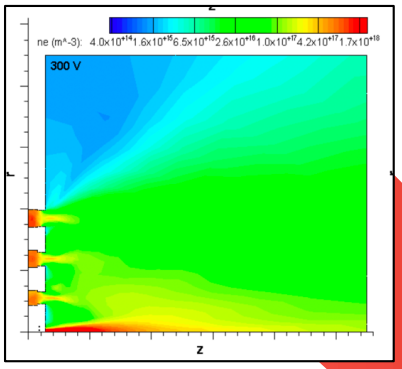
- System had not been demonstrated at 100 kW
- Open questions about extensibility to key program objectives

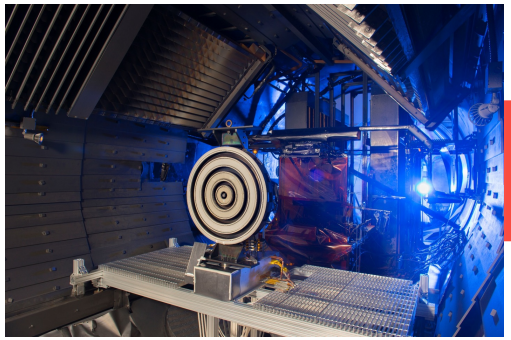
X3: Propulsion element for the XR-100 system

- Merits and history of the X3
- **Year 1 and 2 activities**
- Remaining risk reduction activities

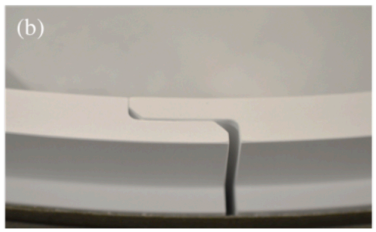
Parallel research paths for Years 1 and 2 activities on X3



Modeling



Testing



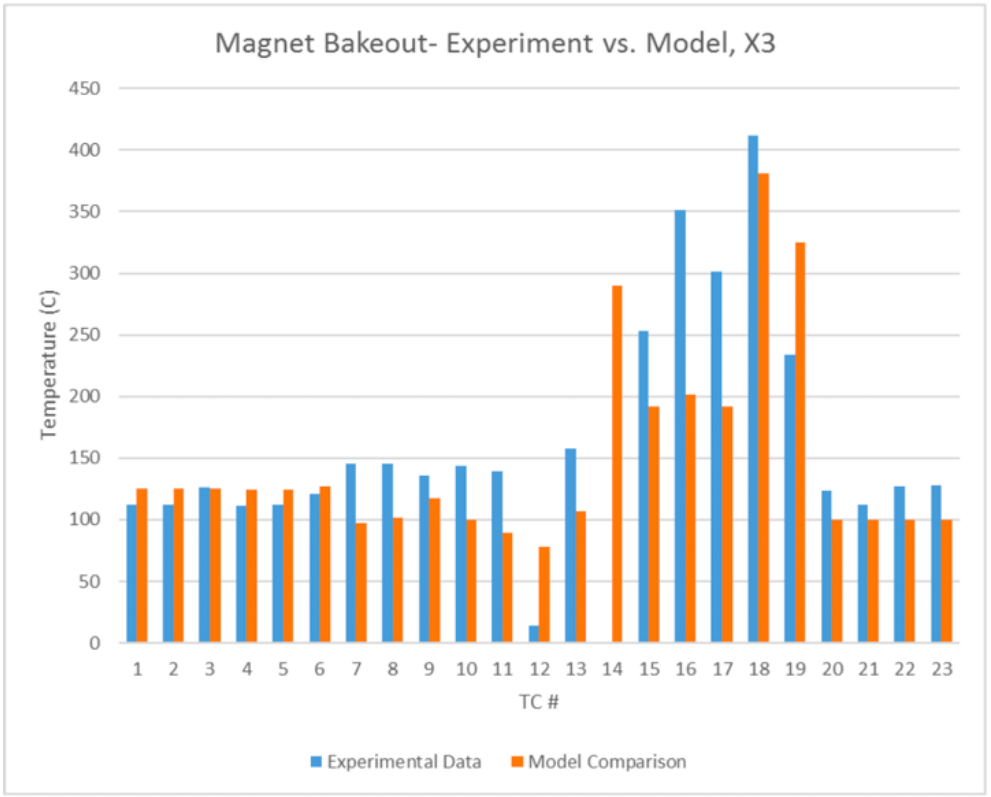
Design modifications

Year 3: 100 h test at 100 kW

Demonstrate extensibility beyond Year 3

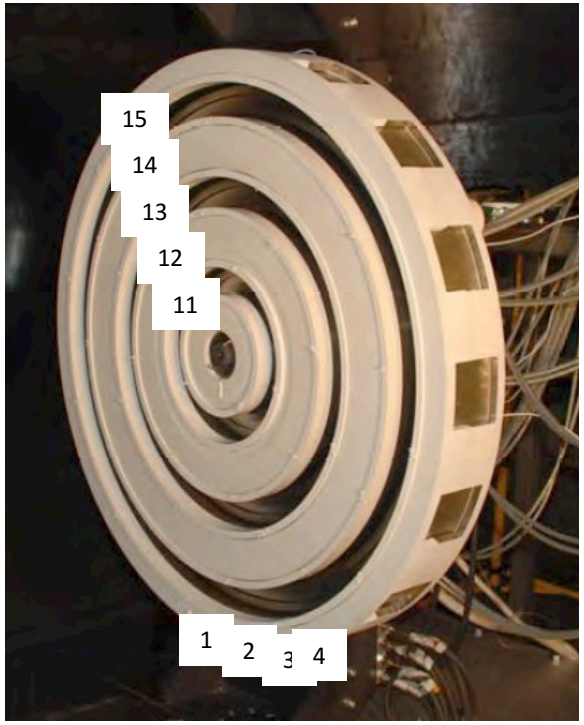
Modeling efforts on X3 to date: thermal

Sample result*



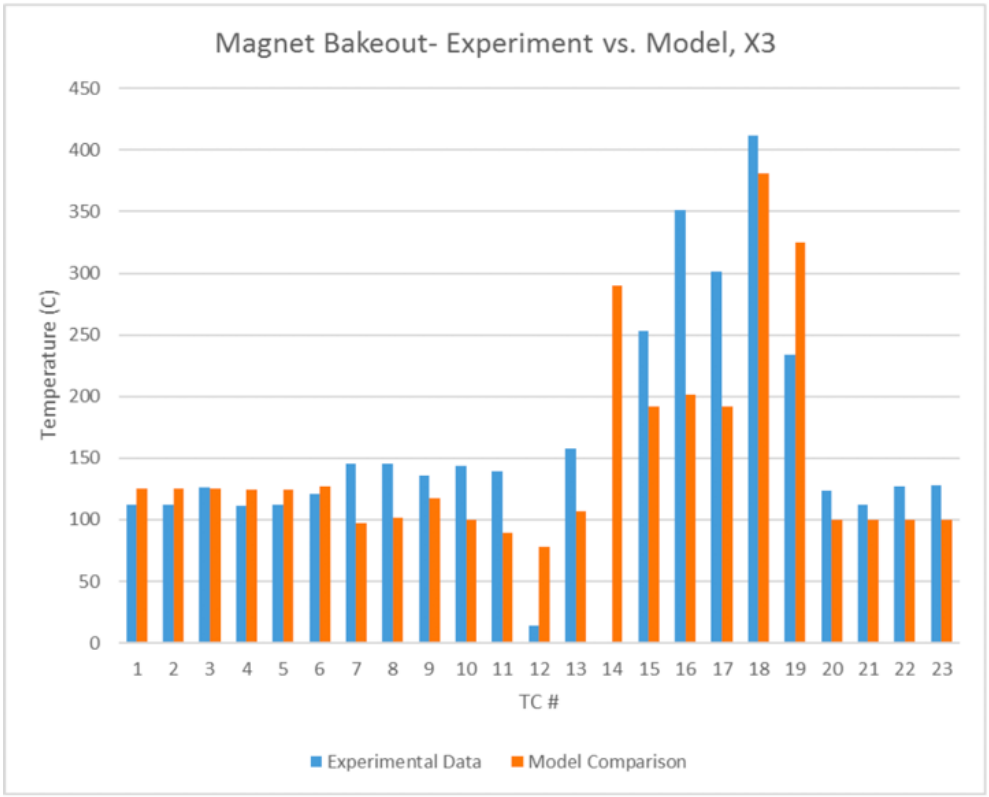
*S. Reilly and R. Hofer. ICES-2017-345

Sample thermal couple placement on X3



Modeling efforts on X3 to date: thermal

Sample result*

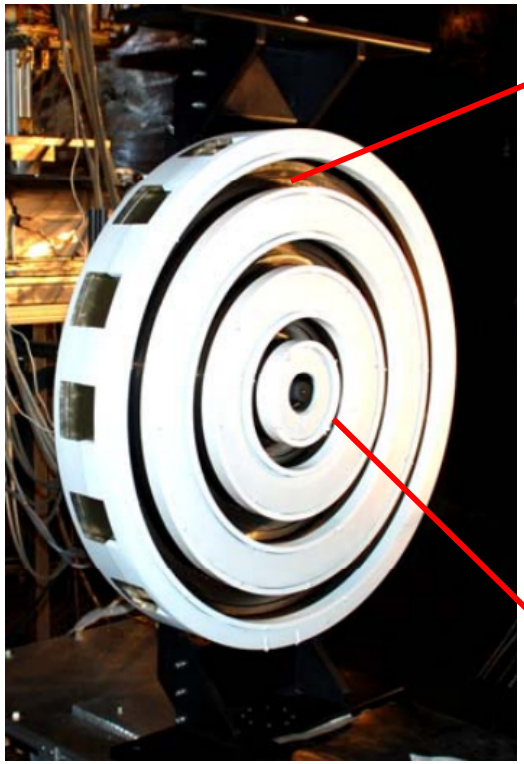


*S. Reilly and R. Hofer. ICES-2017-345

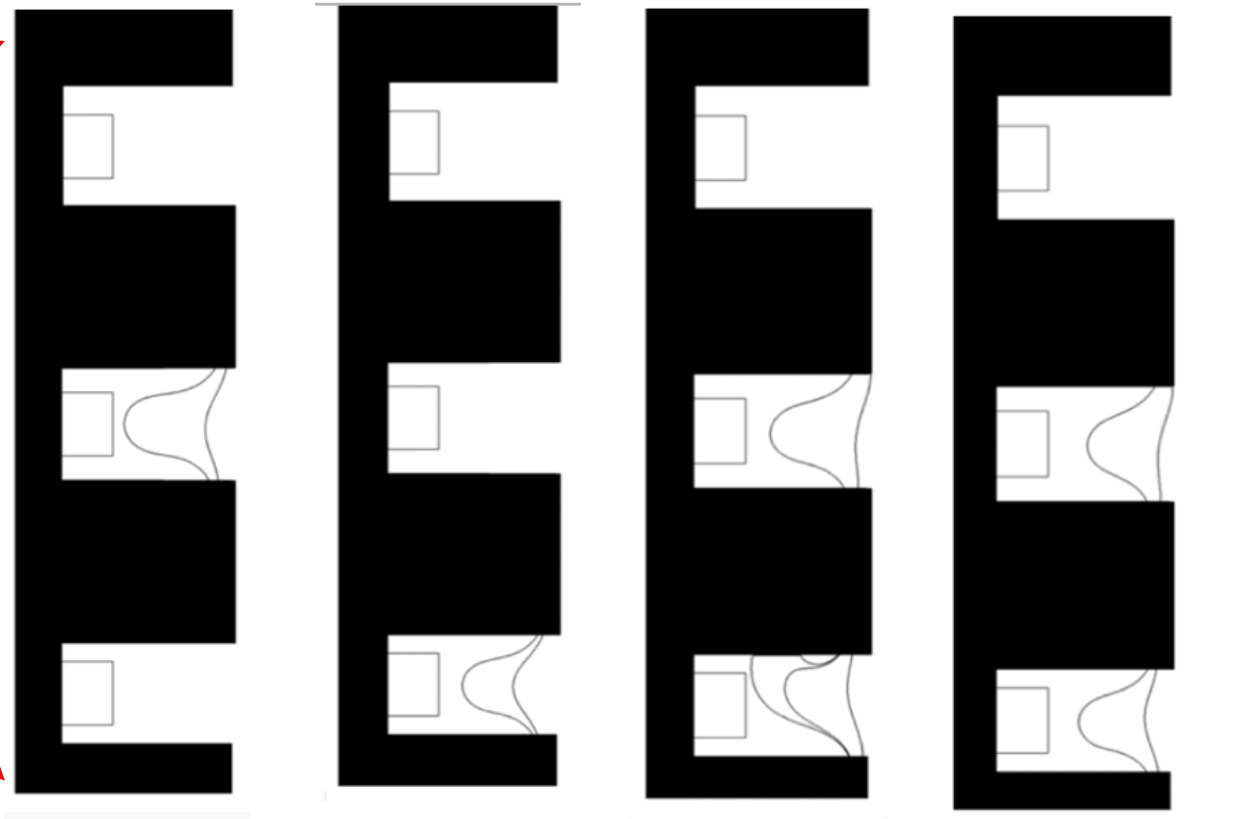
Status

- Thermal model developed and validated against limited data set
- Existing thermal data sets from low-power testing (2016) had not reached thermal equilibrium for model calibration
- *Follow on testing scheduled for Summer 2018 to provide additional calibration data*

Modeling efforts on X3 to date: magnetic field



S. Cusson, S. Hall, R. Hofer, B. Jorns, and A. Gallimore, IEPC-2017-507



Coil current setting 1

Coil current setting 2

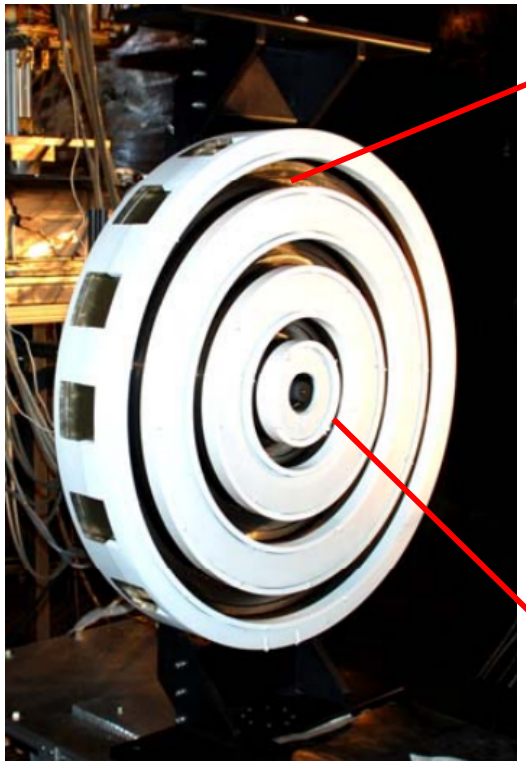
Coil current setting 1+2

Coil current setting (corrected)

Modeling efforts on X3 to date: magnetic field

Status

- Improved and validated magnetic field model generated
- Coil current settings identified for optimized magnetic field configurations
- Configurations demonstrated in 2017 risk reduction test



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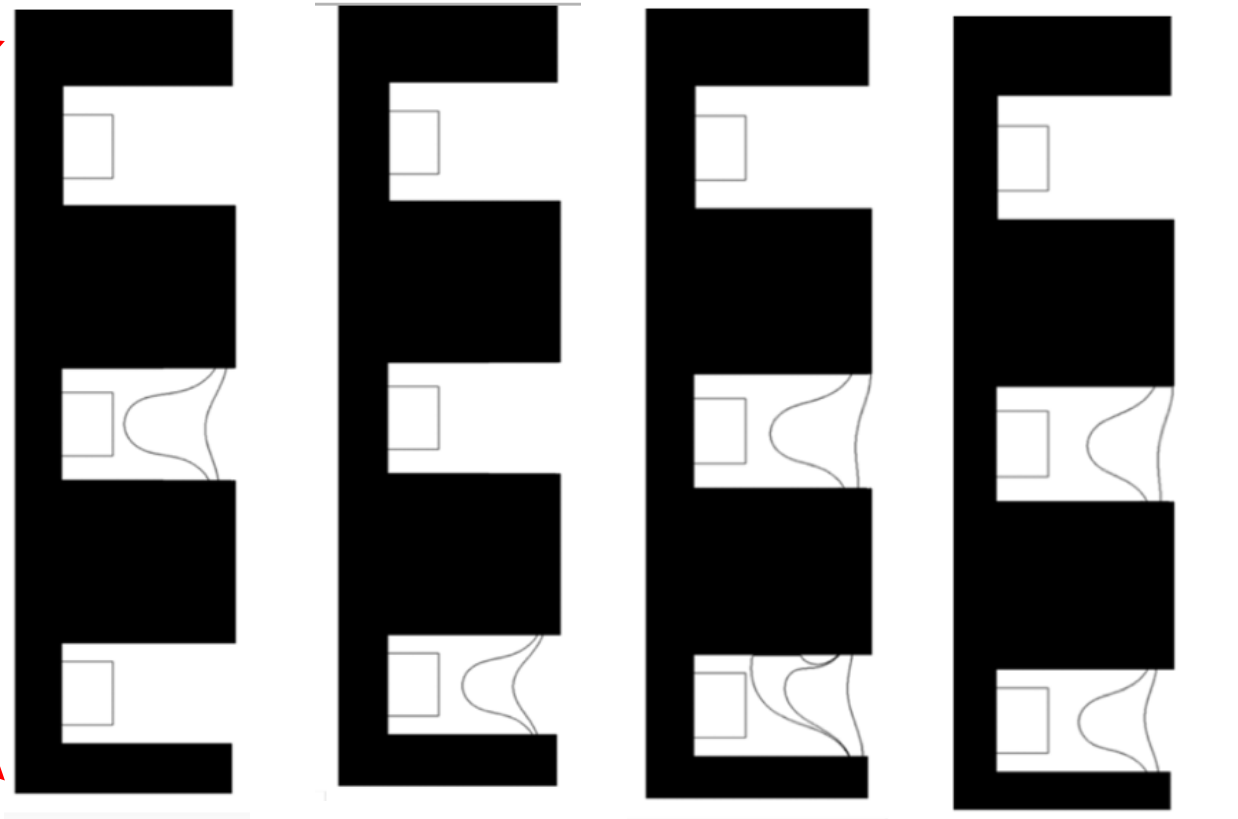


Coil current setting 1

Coil current setting 2

Coil current setting 1+2

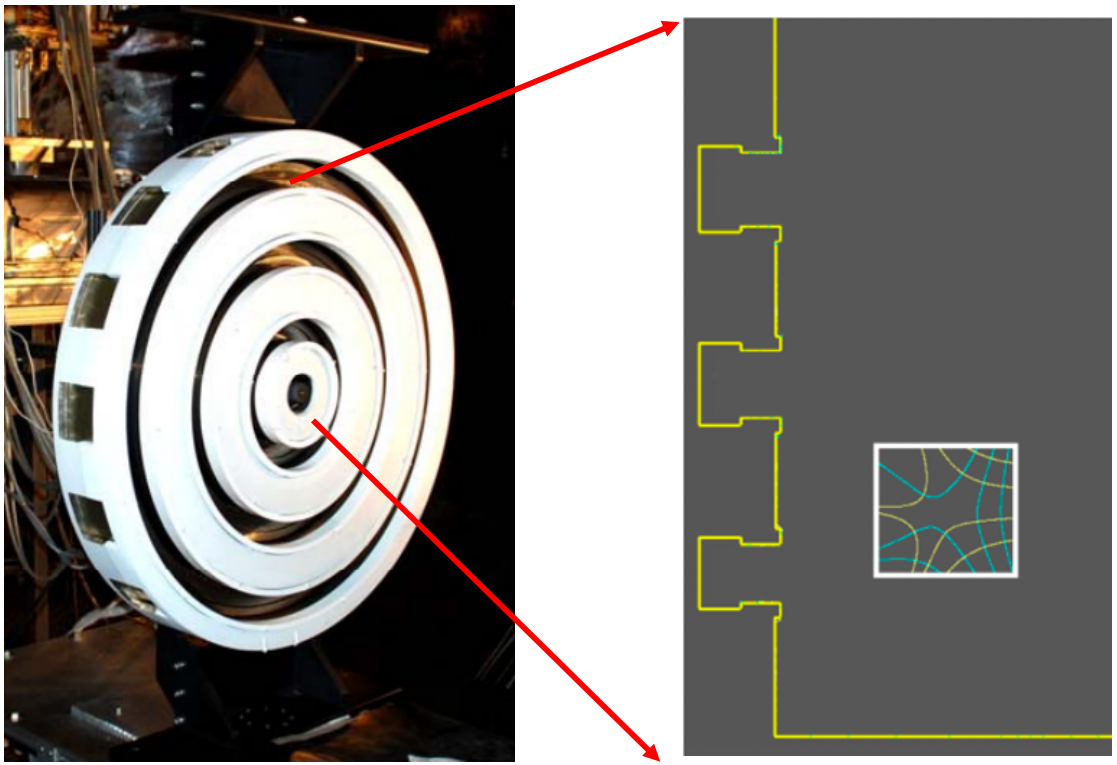
Coil current setting (corrected)

Modeling efforts on X3 to date: plasma

Goals

- Generated experimentally-validated plasma-based model of NHT operation
- Use validated model to assess life and explore design iterations for demonstrating NextSTEP lifetime objectives (10,000 h life)

Notional geometry and meshing in model

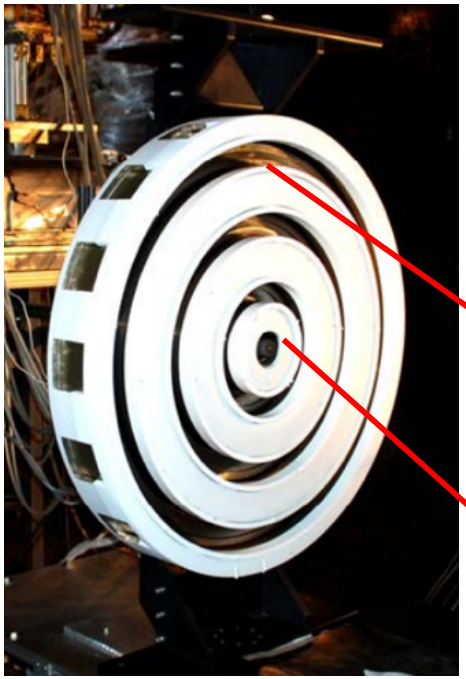


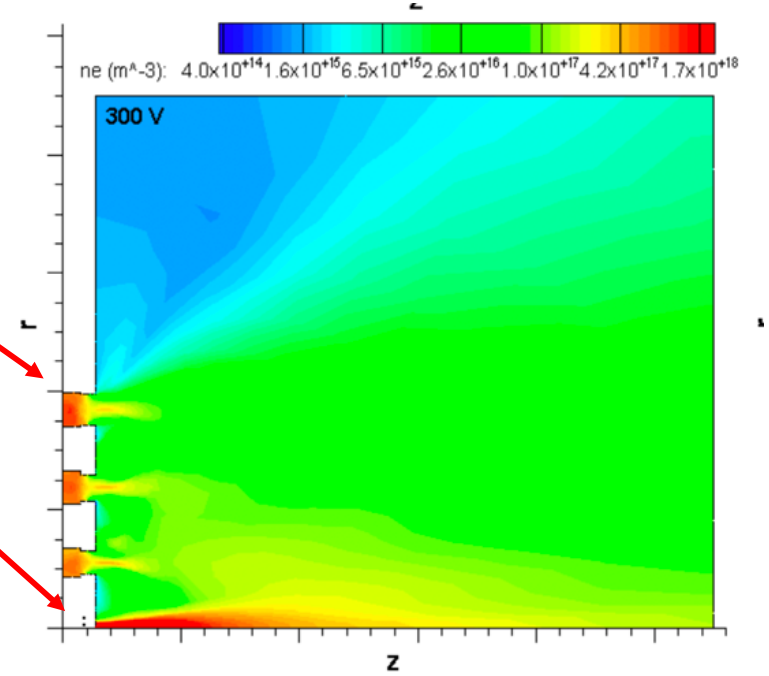
I. Mikellides and A. Lopez-Ortega, IEPC-2017-220

Modeling efforts on X3 to date: plasma

300 V and 100 kW simulation results

Plasma density





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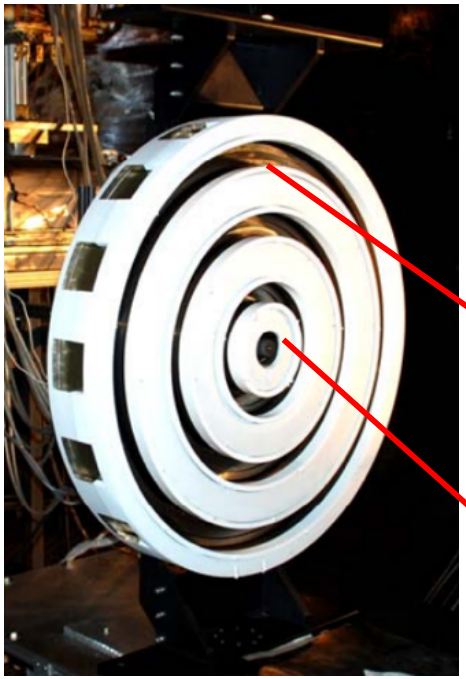

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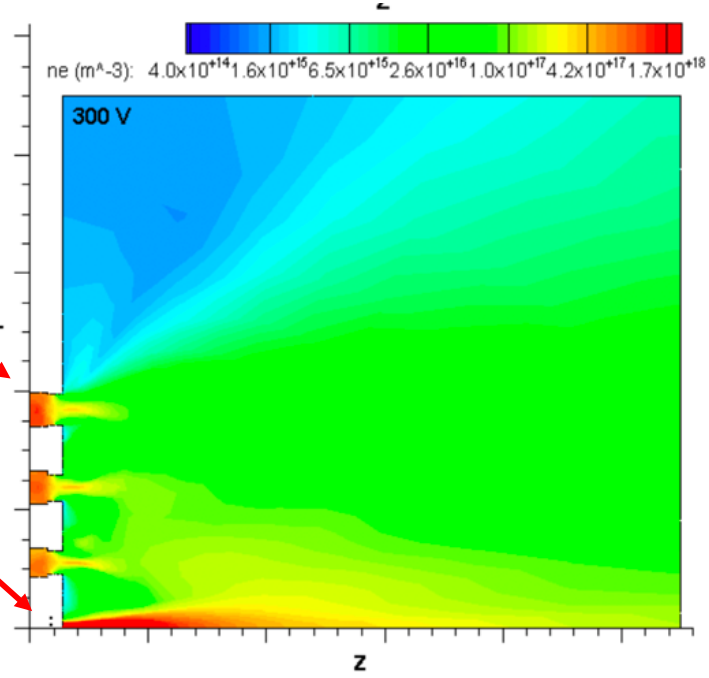
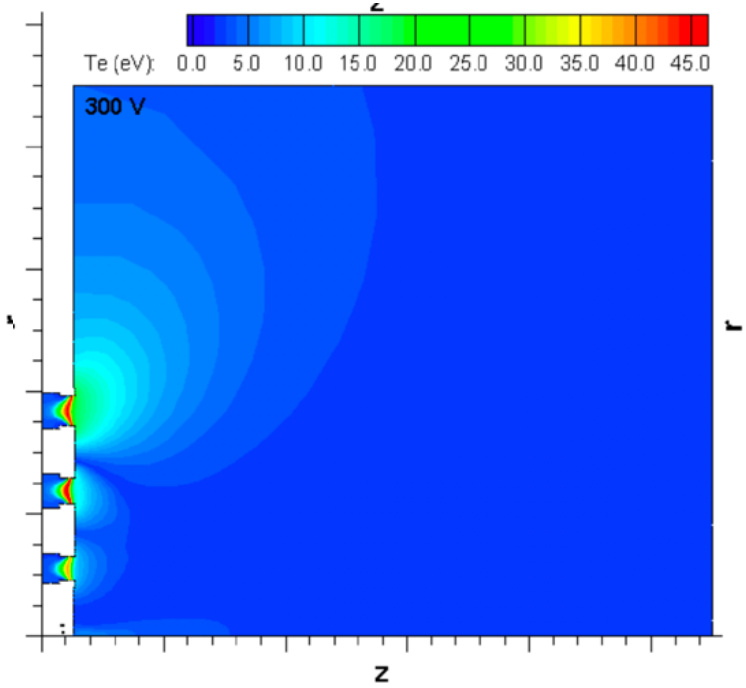


Electron temperature



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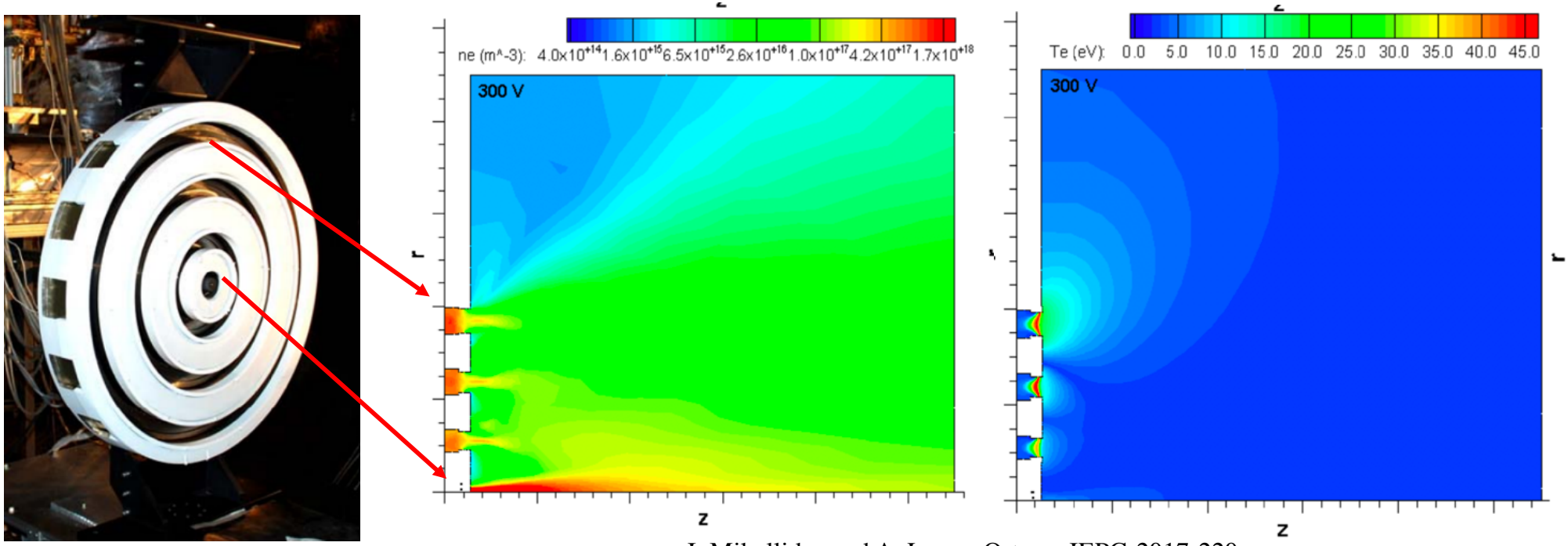

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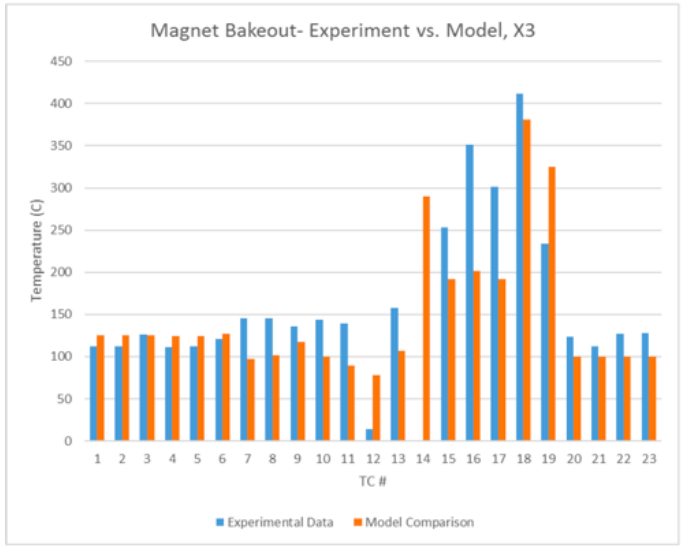
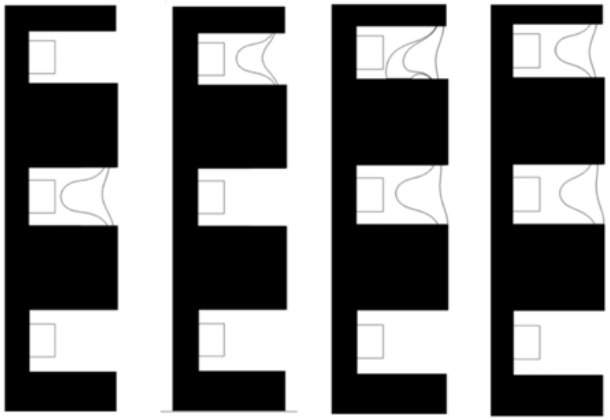
Status

- Model validated against one experimental operating condition (400 V and 49.6 kW)
  - 5% within measured specific impulse
  - 10% measured efficiency
- On-going efforts to validate against other measured operating conditions
- Key missing element is internal plasma measurements (beyond scope of Year 3)

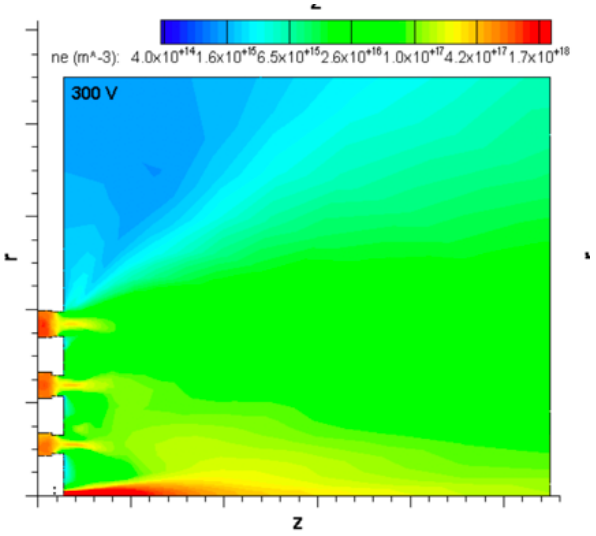
Modeling summary

- Thermal model built and validated against existing data sets. Full calibration pending thermal equilibrium measurements in 2018.



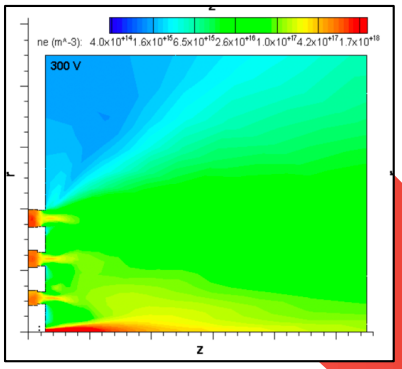


- Magnetic field model built and applied to optimize thruster performance

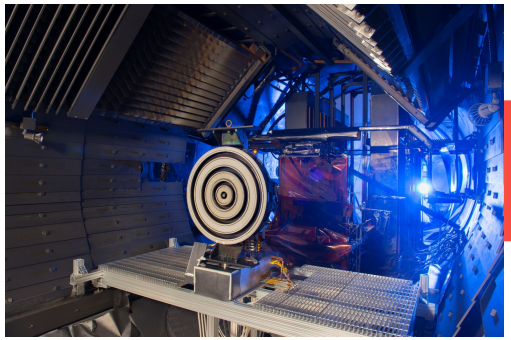


- Plasma model built and validated against one operating conditions. Efforts proceeding to validate against other conditions.

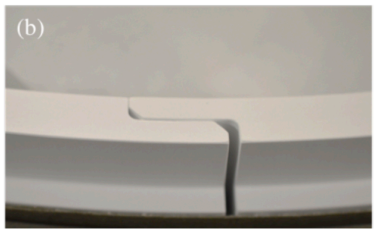
Work path for Years 1 and 2 activities on X3



Modeling



Testing



Design modifications

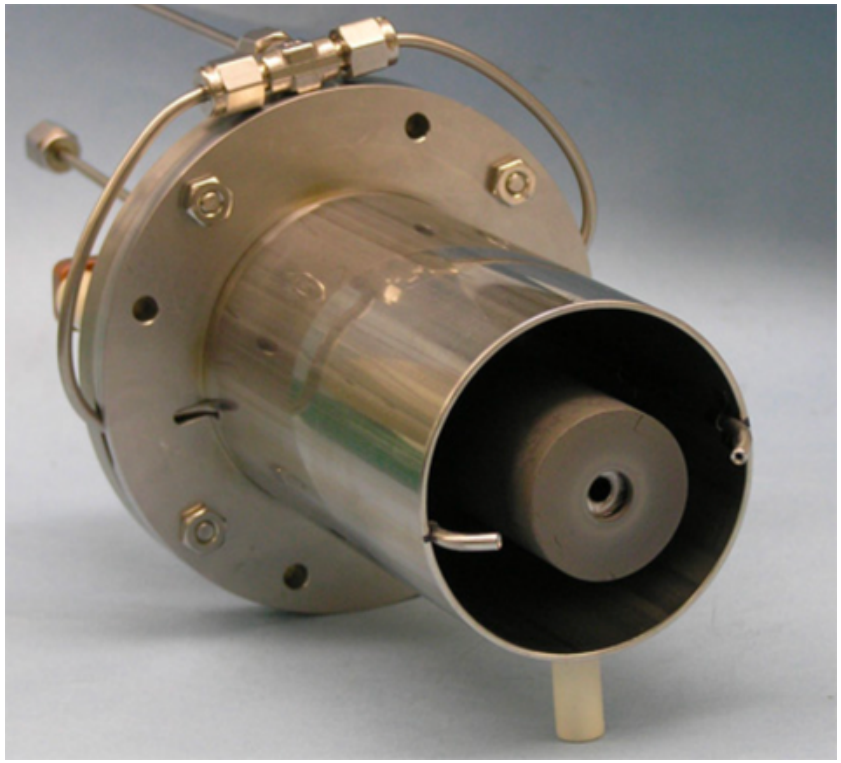
Year 3: 100 h test at 100 kW

Extensibility beyond Year 3

X3 250 A LaB_6 hollow cathode testing

Overview

- Three generations of 250-A class LaB_6 cathode tested during NextSTEP program. All three have sufficient life and performance for 100 h test
- Design iterations in Years 1 and 2 performed to demonstrate extensibility to 10,000 hour lifetime objective of NextSTEP program.
- Characterization testing performed to prove out these features



D. Goebel, G. Becatti, S. Reilly, K. Tilley, and S. Hall, IEPC-2017-303

X3 250 A LaB_6 hollow cathode testing

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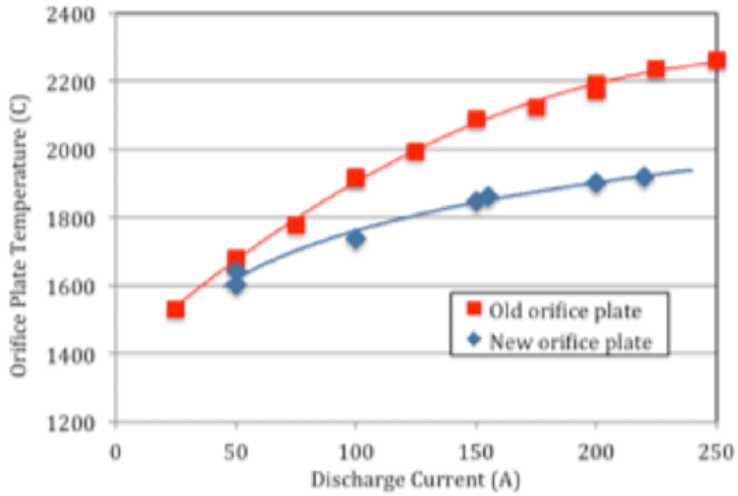
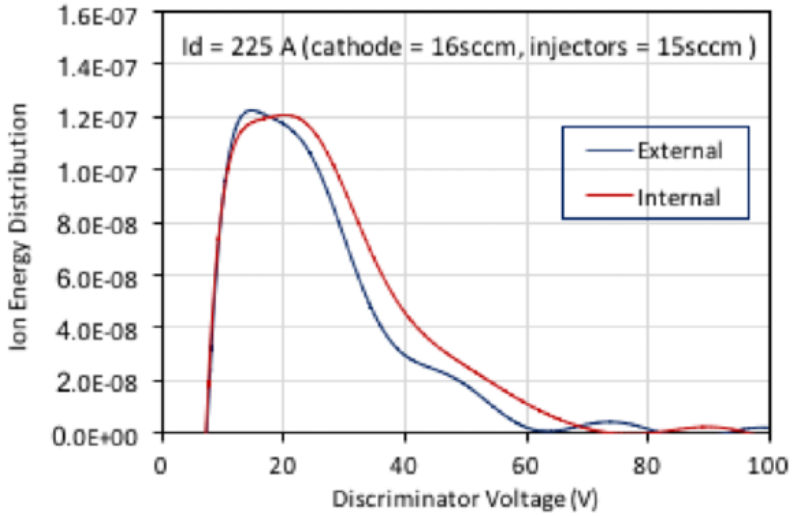
Orifice plate temperature



Ion energy



D. Goebel, G. Becatti, S. Reilly, K. Tilley, and S. Hall, IEPC-2017-303

X3 250 A LaB_6 hollow cathode testing

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- Design iterations in Years 1 and 2 performed to demonstrate extensibility to 10,000 hour lifetime objective of NextSTEP program.
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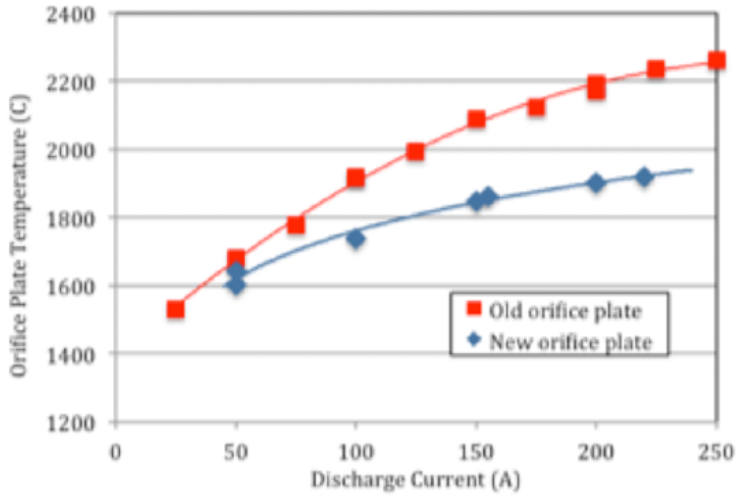
Status: 3rd generation cathode in use on X3. Cathode life now projected to be > 10,000 hours

Orifice plate temperature



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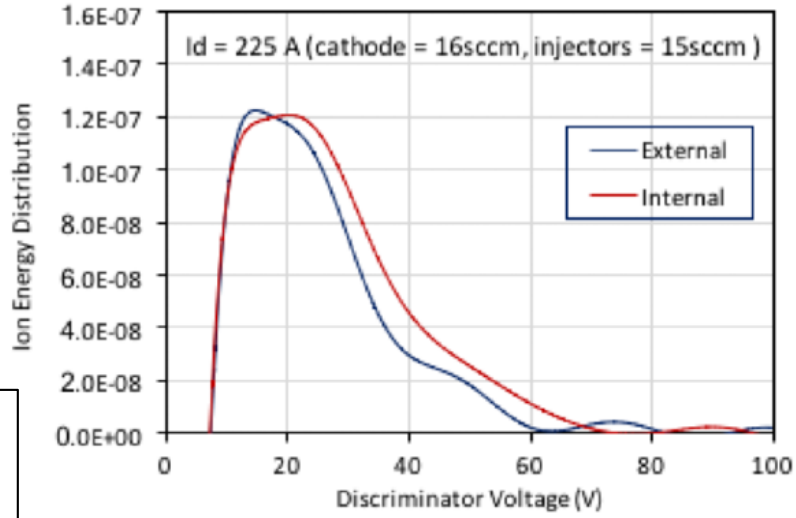

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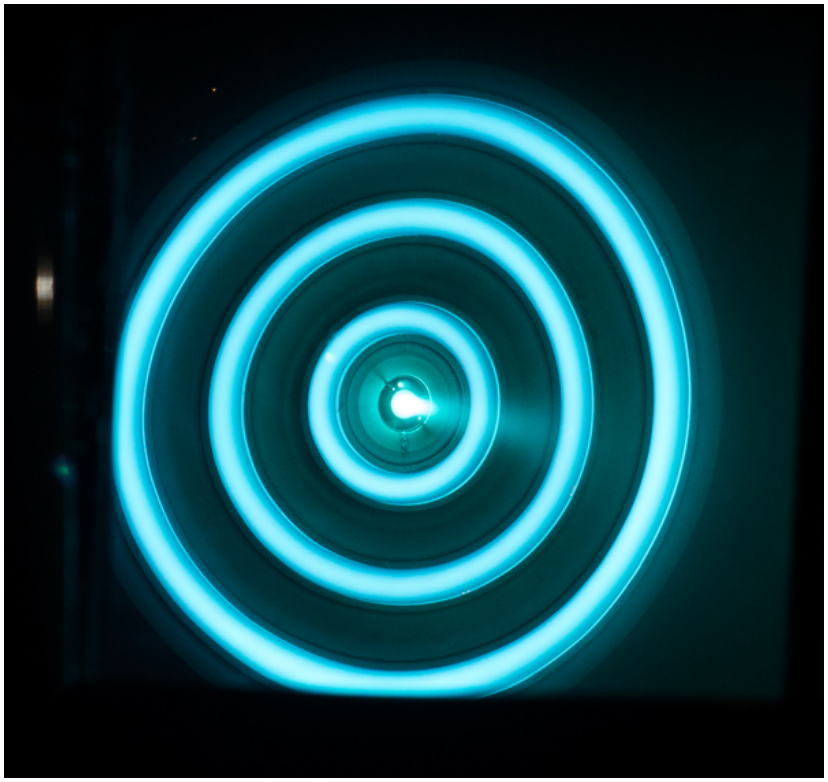
X3 risk reduction test at NASA GRC

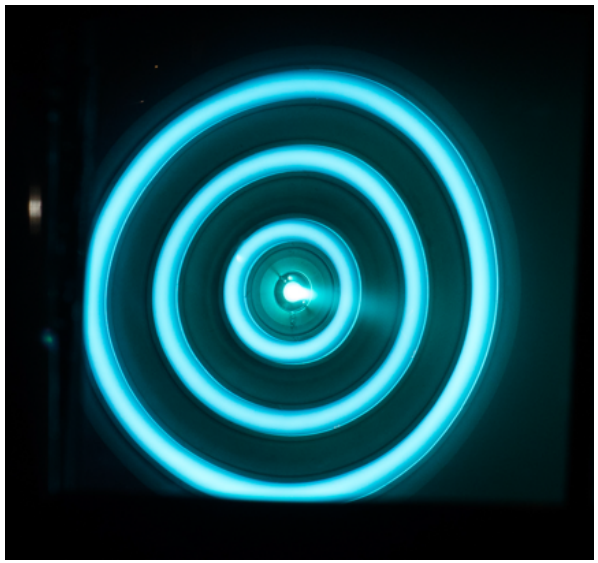
Goals

- Demonstrate thruster for first time at NextSTEP power levels (100 kW)
- Evaluate performance metrics against NextSTEP goals
- Identify any follow on actions for thruster or facility in preparation for 100 h, 100 kW demonstration test.

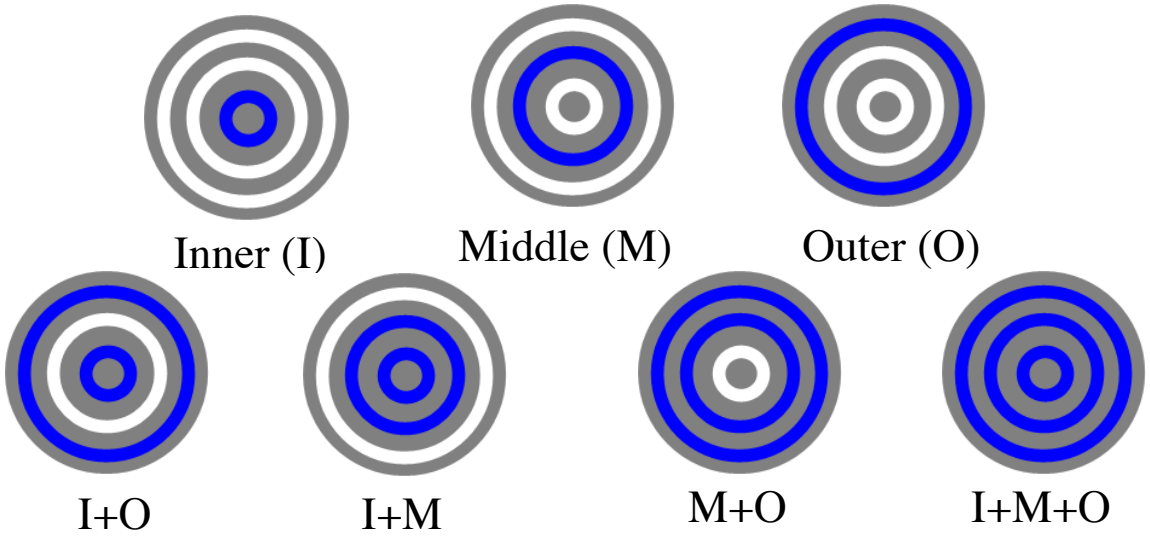


S. Hall, B. Jorns, A. Gallimore, H. Kamhawi, T. Haag, J. Mackey, J. Gilland, P. Peterson, and M. Baird. IEPC-2017-228

X3 risk reduction test at NASA GRC



Thrust throttled through 47 conditions

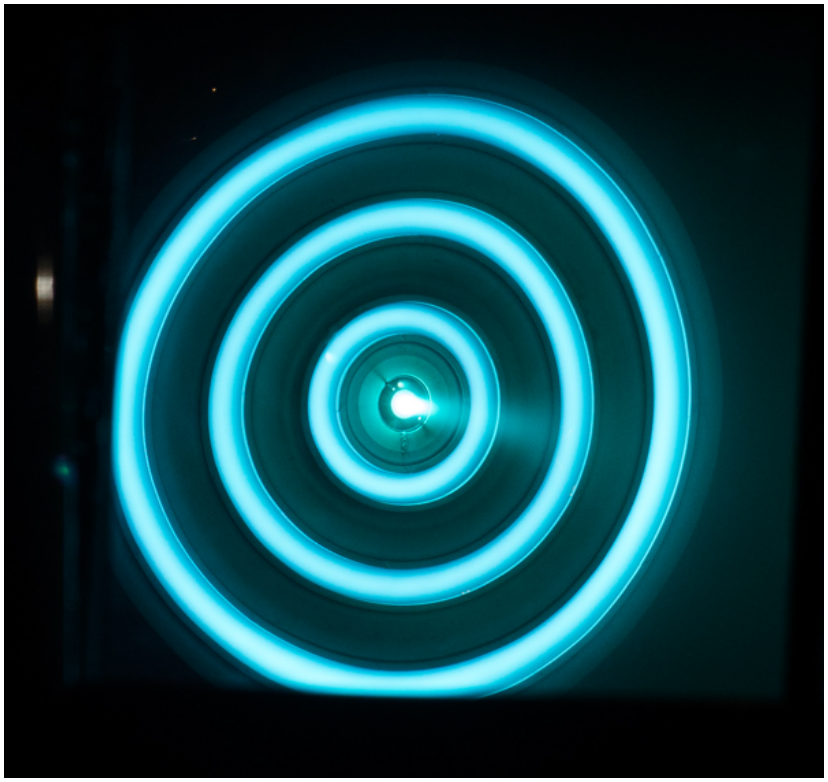


S. Hall, B. Jorns, A. Gallimore, H. Kamhawi, T. Haag, J. Mackey, J. Gilland, P. Peterson, and M. Baird. IEPC-2017-228

X3 risk reduction test at NASA GRC

Goals

- Demonstrate thruster for first time at NextSTEP power levels (100 kW)
- Evaluate performance metrics against NextSTEP goals
- Identify any follow on actions for thruster or facility in preparation for 100 h, 100 kW demonstration test.



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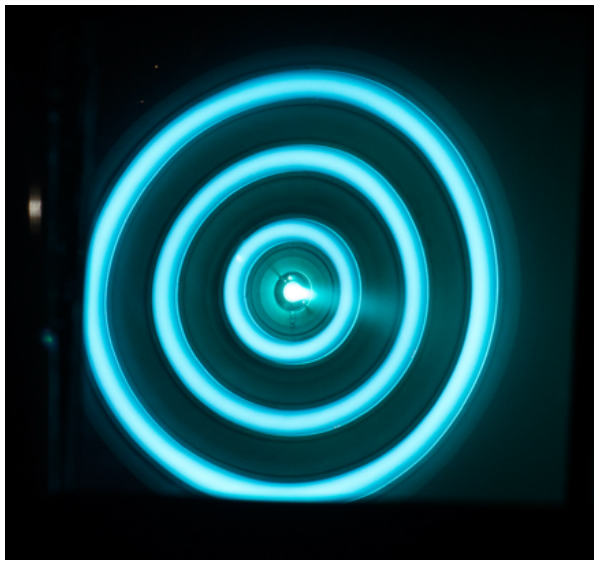
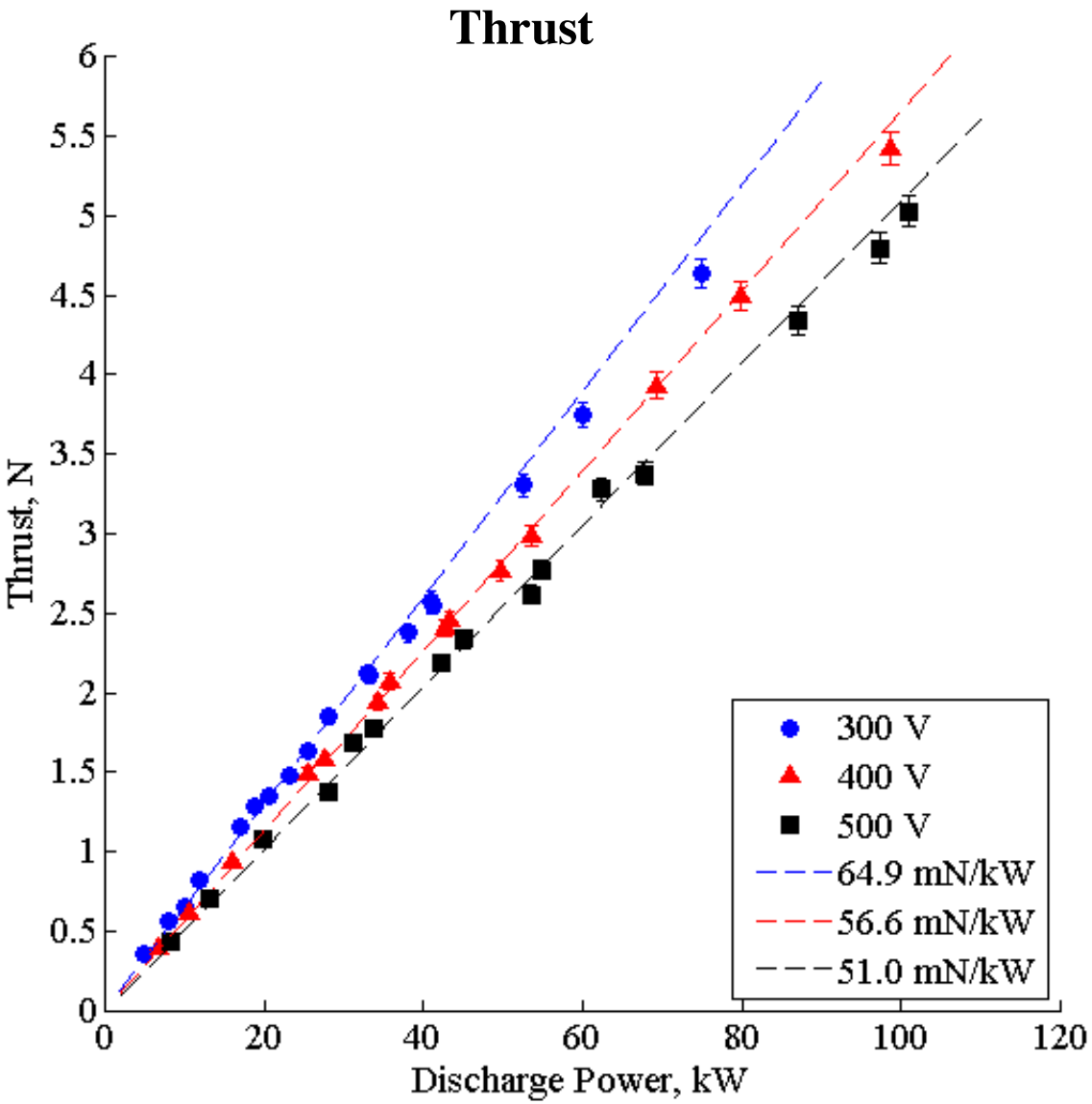
X3 risk reduction test at NASA GRC

Results from 2018 test at NASA GRC*





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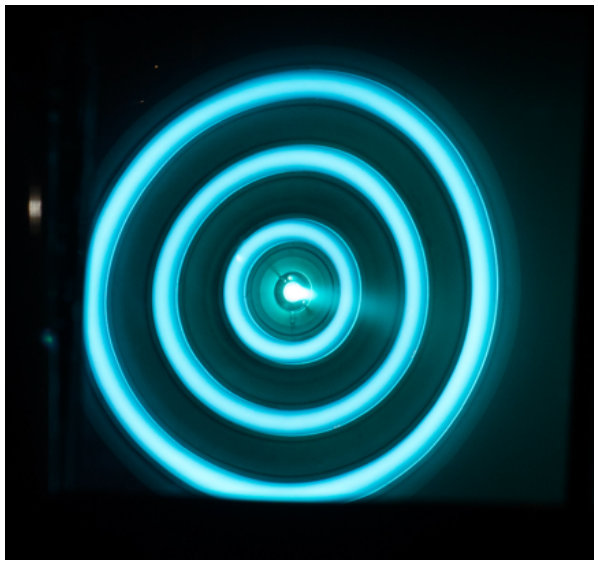
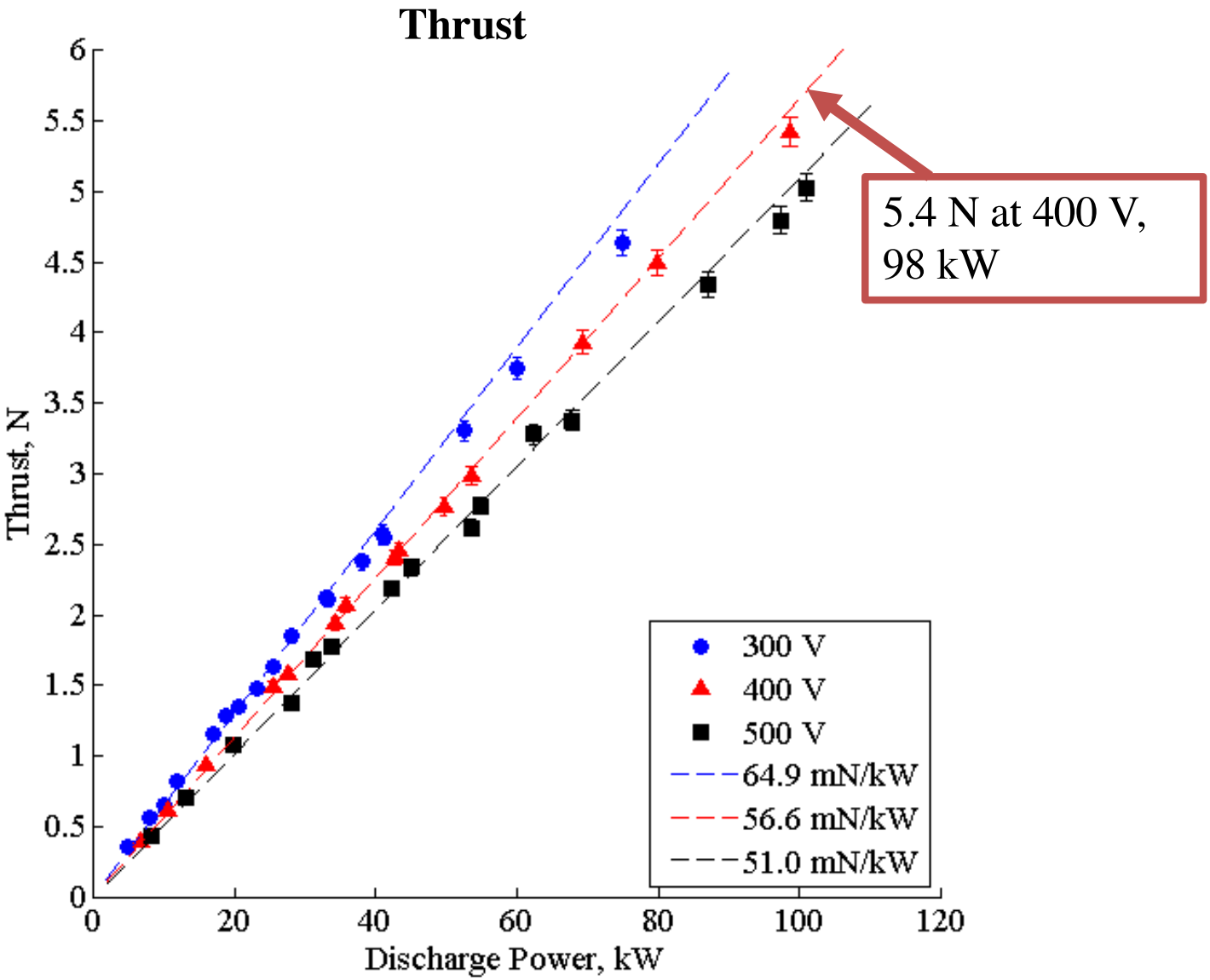
X3 risk reduction test at NASA GRC

Results from 2018 test at NASA GRC*





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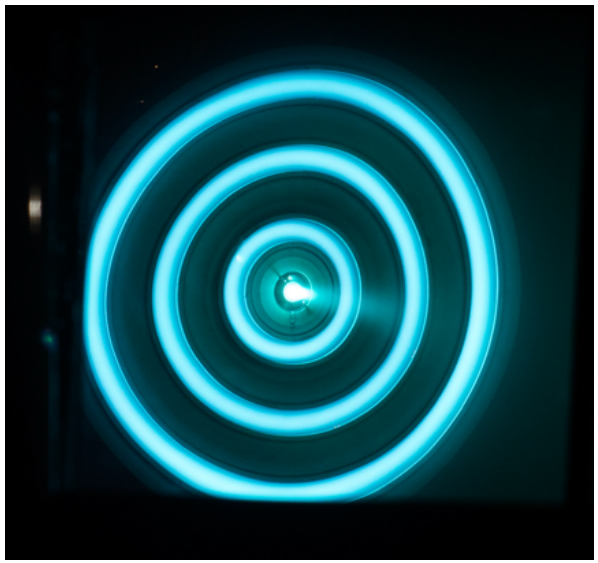
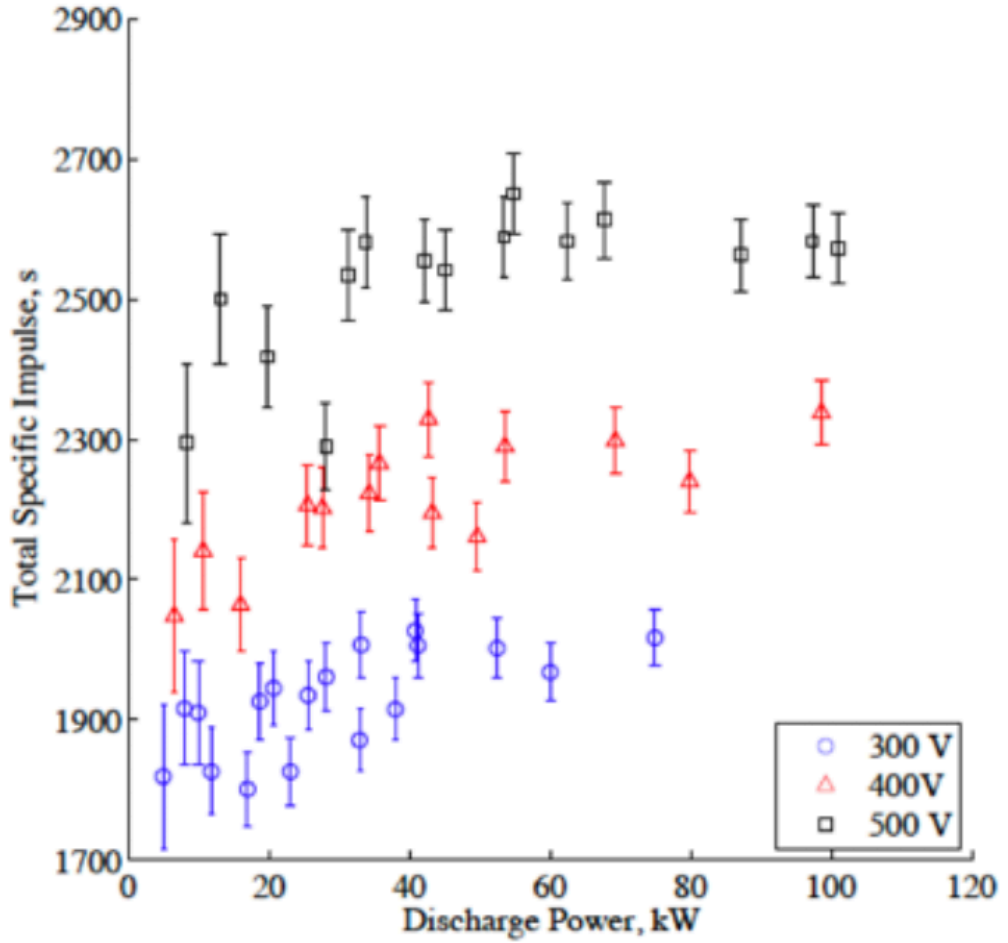


Specific impulse



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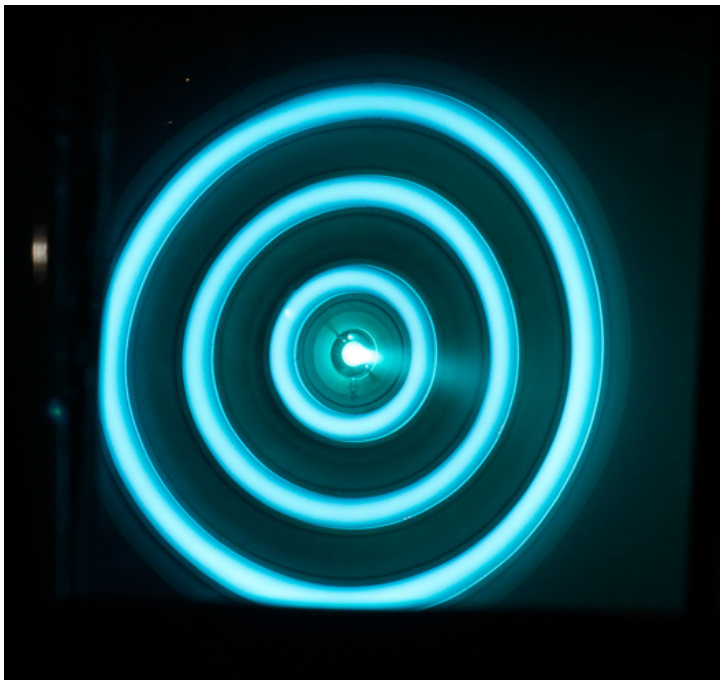
X3 risk reduction test at NASA GRC

Metric		XR-100 Goal
Requirement	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Objective	Specific Impulse	~2,000 to ~5,000 s
	Thrust per thruster	> 5 N
	Operational lifetime capability	> 10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System kg/kW	< 5 kg/kW

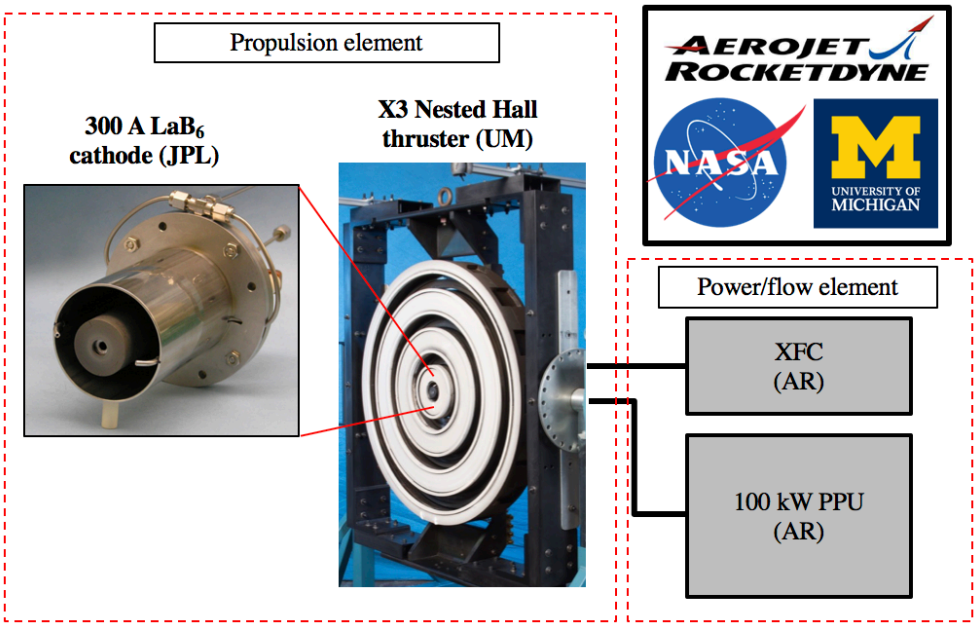


Demonstrated thrust at 100 kW: 5.4 ± 0.1 N
Demonstrated specific impulse at 100 kW: 2600 s
Demonstrated efficiency at 100 kW: 67%

10-kW systems level test

Overview

- Demonstrate X3 system commanded and controlled by Aerojet DSU and XFC
- Only inner channel operated at 10 kW

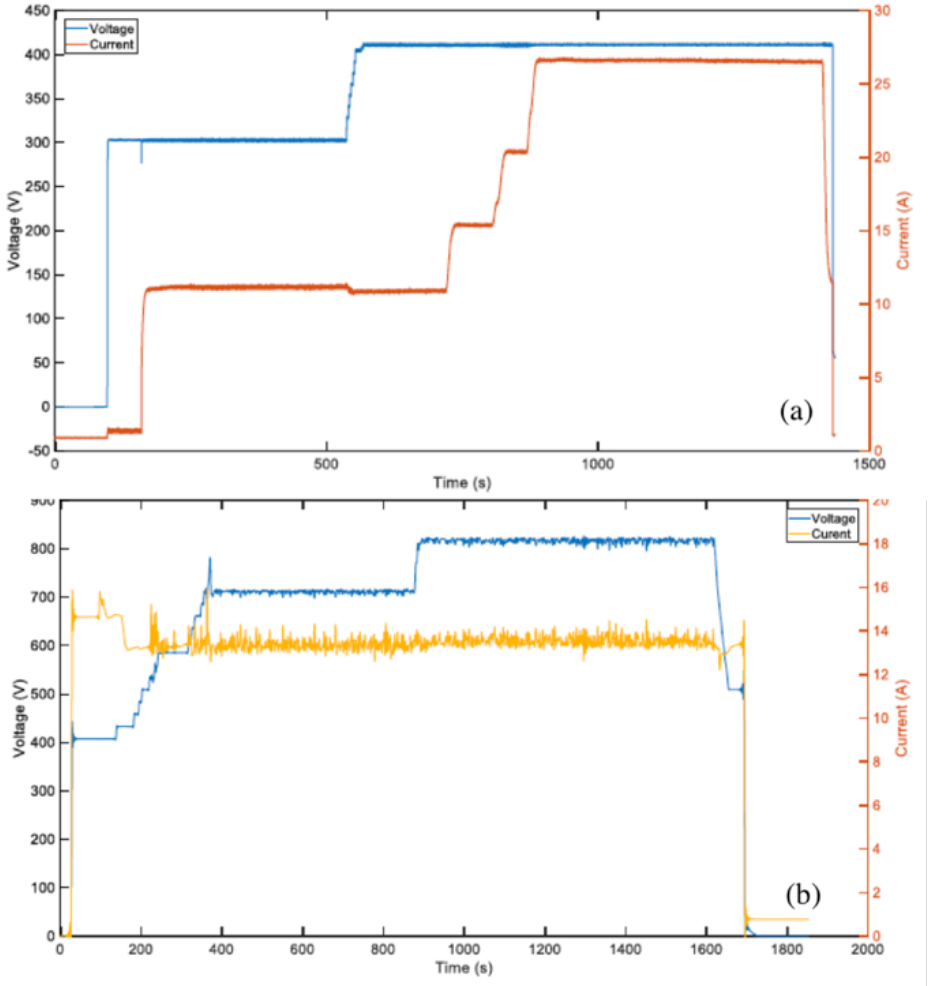


S. Shark et al. , "Test Resuls from a 10 kW Demonstration of the XR-100 Hall Propulsion System," in 65th Joint Army Navy NASA Air Force Propulsion Meeting, Long Beach, CA , 2018

10-kW systems level test

Status

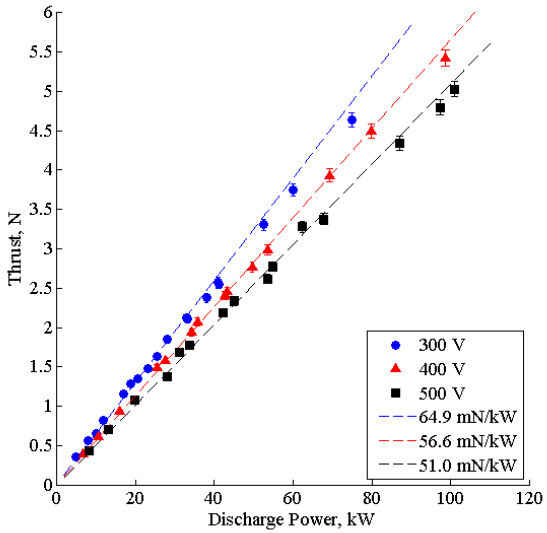
- Test conducted at University of Michigan in January 2018
- Paper on it in this session (AIAA-2018-4419)
- New understanding of load impedance and transients informing Year 3 developments

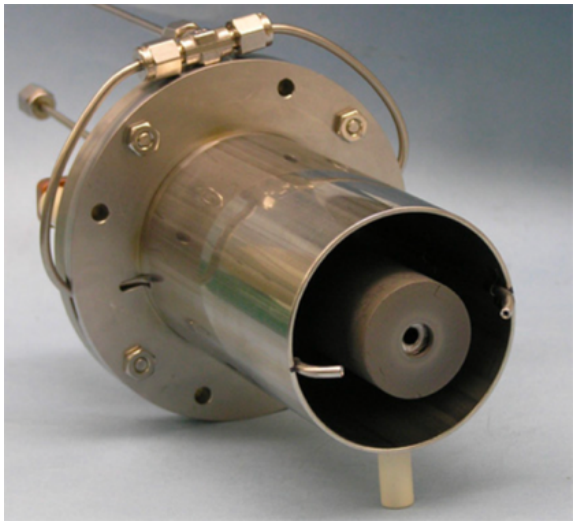


S. Shark et al. , "Test Results from a 10 kW Demonstration of the XR-100 Hall Propulsion System," in 65th Joint Army Navy NASA Air Force Propulsion Meeting, Long Beach, CA , 2018

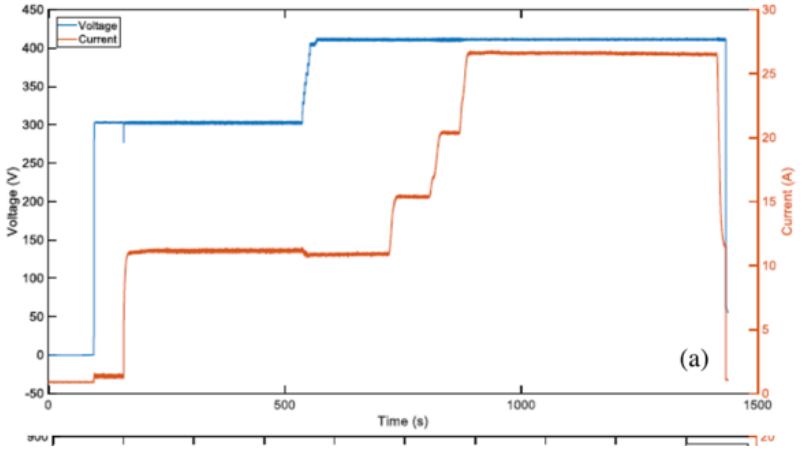
Testing summary

- Third-generation LaB_6 hollow cathode design tested and lifetime projected to be > 10,000 h



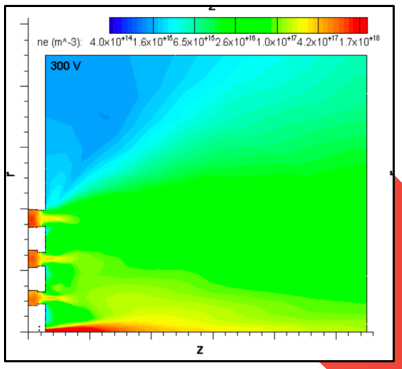


- Risk reduction test on X3 performed at NASA GRC and demonstrated thruster performance at 100 kW

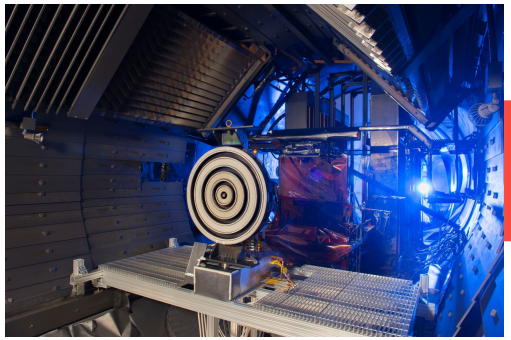


- Systems level test demonstrated XR-100 capability at reduced power (10-kW)

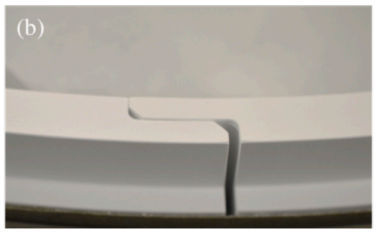
Work path for Years 1 and 2 activities on X3



Modeling



Testing



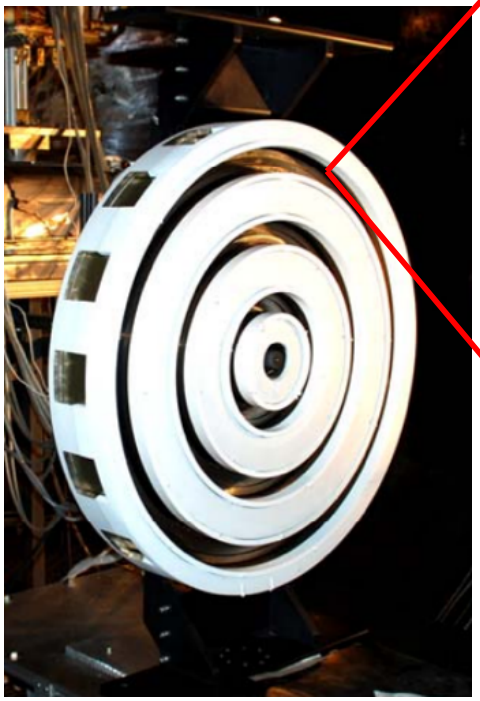
Design modifications

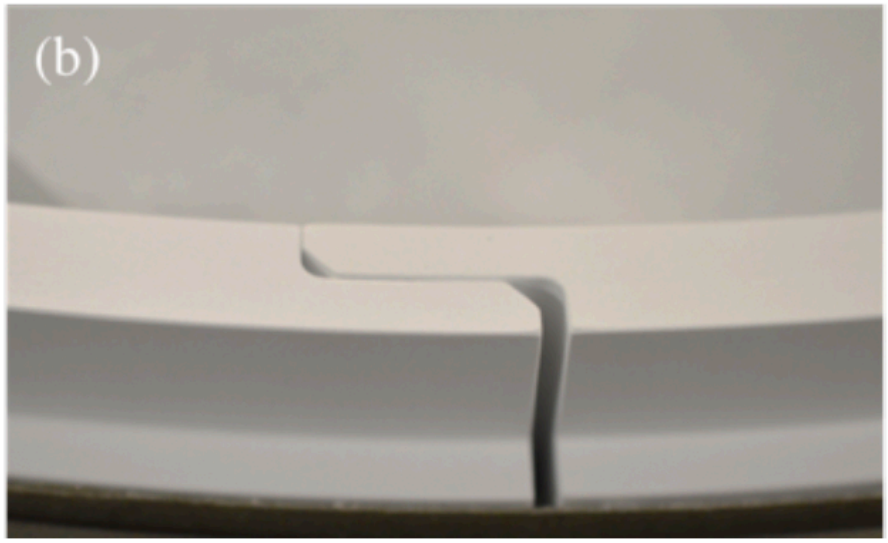
Year 3: 100 h test at 100 kW

Extensibility beyond Year 3

Design modifications

- Demonstrate a discharge chamber ring modification at temperature
- Demonstrate ring modification works at high voltage (> 700 V)
- Generate additional thermal steady-state data for model validation





X3: Propulsion element for the XR-100 system

- Merits and history of the X3
- Year 1 and 2 activities
- **Remaining risk reduction activities**

Final risk reduction test

X3 with new ring design installed in upgraded LVTF at UM (June 2018)

Thruster has passed reference firing conditions. Currently performing high-voltage tests.

Summary

- **XR-100 one of three selected technologies for NextSTEP program. Goal is to advance system to TRL 5 in three years.**
- **X3 is a Nested Hall Thruster (NHT) propulsion element for the XR-100**
- **Efforts on X3 subsystem in Years 1 and 2 have focused on**
  - Modeling development
  - Risk reduction testing
  - Low power systems level demonstrations
- **Thruster has demonstrated performance levels meeting NextSTEP requirements (thrust, efficiency, specific impulse)**
- **Small design modifications identified during 2017 RRT and have been implemented. Modifications undergoing final risk reduction test at UM now**
- **Thruster subsystem is on track for demonstration in late 2018 100 h, 100 kW test.**

Acknowledgements

AEROJET ROCKETDYNE
NASA
UNIVERSITY OF MICHIGAN

PEPL Lab Group 2018